Technology Readiness Levels for the New Millennium Program

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Abstract— National Aeronautic and Space Administration's (NASA) New Millennium Program (NMP) seeks to advance space exploration by providing an in-space validating mechanism to verify the maturity of promising advanced technologies that cannot be adequately validated with Earth-based testing alone. In meeting this objective, NMP uses NASA Technology Readiness Levels (TRL) as key indicators of technology advancement and assesses development progress against this generalized metric. By providing an opportunity for in-space validation, NMP can mature a suitable advanced technology from TRL 4 (component and/or breadboard validation in laboratory environment) to a TRL 7 (system prototype demonstrated in an Earth-based space environment). Spaceflight technology comprises a myriad of categories, types, and functions, and as each individual technology emerges, a consistent interpretation of its specific state of technological advancement relative to other technologies is problematic. The resulting ambiguity forms an inconsistent basis on which to judge a new technology's TRL. To qualify for consideration by NMP, the technology must have at least achieved TRL 3 (analytical and experimental critical function and/or characteristic proof-of-concept achieved in a laboratory environment). The TRLs used by NMP are the same as those in general use at NASA. The criteria used by NMP to determine when a given TRL is reached are added to their description and are described here. The specific criteria for exit gates have become better defined as NMP itself has evolved. A brief summary of the NMP history shows how NMP missions have evolved, thus making the consistent interpretation of TRLs increasingly important. The notion of the "relevant environment" is specifically emphasized, wherein relevant environment refers to the environment that adequately stresses the technology in order to provide sufficient confidence in its testing. The TRL of a given technology is based on the environment in which the technology has been tested and validated—beginning in the laboratory, advancing through ever-improving simulation and testing, until finally achieving actual in-space validation.

A corollary to what qualifies as a specific technology readiness is the pervasive confusion that exists between what is actually new technology and what is development, which this paper hopes to clarify. An assigned TRL pertains to the status of the technology itself, not to a particular stage in the design and fabrication of a specific item. If new physics elements are being applied or if combined effects from conventional elements create a new function never before experienced, then an item is new technology and the TRL may be very low. However, if the components and subsystems being designed are based on known quantities, and the end product will function within experienced operating ranges that demonstrate effects similar to those of components already flown, then this process is development and the TRL would be fairly high—regardless of the difficulty of producing the product. This is the interpretation of the TRLs that the present NMP flight-validation selections are following.

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1. INTRODUCTION

In 1995, the National Aeronautics and Space Administration (NASA) created the New Millennium Program (NMP), and the Jet Propulsion Laboratory (JPL) was assigned to manage the program for NASA. NMP's objective is to conduct space flight validation of breakthrough technologies for future space- and Earth-science missions. The breakthrough technologies selected for validation must (1)

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enable new science capabilities to fulfill NASA's Space- and Earth-Science Enterprise objectives and/or (2) reduce the costs of future space- and Earth-science missions. The space-flight validation objective of these technologies is to mitigate the risks to the first users and to promote the rapid infusion of these technologies into future science missions. The goal of NMP is to mature a technology requiring flight validation from a Technology Readiness Level (TRL) 4 (component and/or breadboard validation in laboratory environment) to a TRL 7 (system prototype demonstrated in a space environment). Spaceflight technology comprises a myriad of categories, types, and functions, and as each individual technology emerges, a consistent interpretation of its specific state of technological maturity relative to other technologies is problematic. This often results in an inconsistent basis on which to judge a new technology's TRL. The purpose of this paper is to communicate the NMP criteria for judging TRLs so that participants can develop accurate and consistent plans and estimates. To qualify for consideration by NMP, the technology must have at least achieved TRL 3 (analytical and experimental critical function and/or characteristic proof-of-concept achieved in a laboratory environment). While the TRLs used by NMP are the same as those in general use at NASA, NMP has developed criteria used by the program to judge when each TRL has been reached. These supplemental criteria are described here. The specific criteria for exit gates have become better defined as NMP itself has evolved. Additional information on the New Millennium Program is available via the Internet [1].

This paper presents a brief historical overview of NMP's technology validation missions to provide a clearer perspective of how the interpretation of the TRLs has evolved with the maturation of NMP itself. The first generation NMP missions included Deep Space 1 (DS1), Deep Space 2 (DS2), and Earth Observing 1 (EO1). These missions were designed to provide a comprehensive, system-level validation of suites of interacting, high-priority spacecraft and measurement technologies. The second-generation NMP missions began with Space Technology 5 (ST5) and Earth Observing 3 (EO3). These missions also focused on system-level validations, but the elected suites of technologies were selected through a revised process. While the NMP will continue in-space, system-level technology validation missions, such missions are augmented with more highly focused, subsystem-level validation flights of breakthrough technology subsystems. Brief descriptions of the first and second-generation NMP flights and a summary of future flight opportunities are given below. We then describe the NMP interpretation of the TRLs, keeping in mind the distinction between development maturity and technological maturity.

2. First Generation Validation Flights

Deep Space 1

DS1, the first of the New Millennium missions, was launched from the Kennedy Space Center on October 24, 1998. This spacecraft, depicted in Figure 1, carried a complement of technologies that were validated during the 10 months following launch (see Table 1).

Table 1. Technologies Validated by DS1

Technology Validated	Key Technology Advance
Autonomous Optical Navigation	Validated autonomous command and control of spacecraft thrusting and attitude control system to demonstrate capability of maintaining desired course heading without human intervention.
Low-Power Electronics	Validated mission-life performance of fully depleted silicon-on-insulator (SOI) electronics.
Ion Propulsion Subsystem (including diagnostic sensor suite)	Validated that ion-thruster ground testing provided a conservative testing environment as compared with space.
Solar Concentrator Arrays with Reflective Line Element Technology (SCARLET)	Proved that concentrator solar array technologies embodying substantial mass and cost reductions could be deployed and operated in space while achieving performance levels that closely agree with model-based predictions.
Beacon Monitor Operations Experiment	Generated tones depicting spacecraft health to indicate urgency of need for DSN coverage.
Remote Agent Experiment	On-board artificial intelligence system for planning and executing spacecraft activities based on high-level goals.
Multifunctional Structure	Validated new paradigm for integrating electronics within structural panel, easing temperature control, and promising simplified future spacecraft.
Small Deep Space Transponder	Validated single-package combination of receiver, command detector, telemetry modulator, exciter, and beacon-tone generator allowing X-band uplink, and X-band and Ka-band downlink for factor of two mass savings.
Ka-Band Solid-State Amplifier	Validated capability and established feasibility for very small, lightweight amplifier to communicate in Ka band.
Miniature Camera and Spectrometer	Compact science instrument with four imaging instruments sharing a common foreoptic.
Plasma Experiment for Planetary Exploration	Combined multiple instruments to validate a compact plasma-physics suite integrated into a single package with significant mass and power savings over that of comparable technology.

These technologies and the DS1 mission are described in more detail in references 2 and 3. Detailed validation reports for each of these technologies are available on the JPL technical reports server [4].

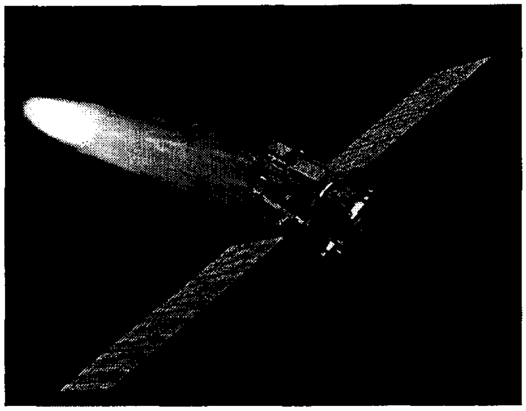

Figure 1 - DS1 contains 11 technologies for space flight validation. The spacecraft intercepted Asteroid 1996 Braile on July 29, 1999; the technology validation mission was completed the following September. DS1 completed the science-mission objective of intercepting Comet Borrelly on September 23, 2001.

Deep Space 2

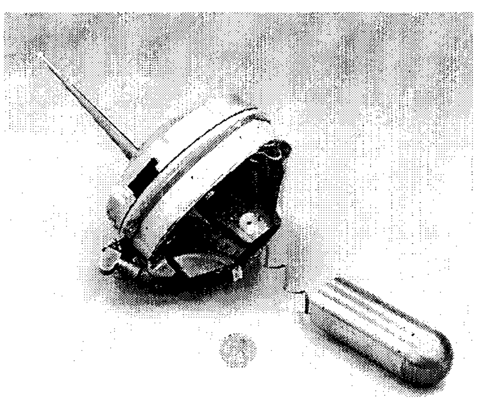

Figure 2 - DS2 Mars Microprobe. At impact, the aft-body (left) would remain on the Martian surface, and the fore-body (right) would penetrate up to one meter into the subsurface soil to detect the presence of water. A multi-layer flex cable connects the two sections.

DS2, the second of the New Millenium missions, was launched from the Kennedy Space Center on January 3, 1999, and arrived at Mars on December 3, 1999. The objectives of this mission were to validate design rules and principles and to demonstrate (1) a passive reentry system, (2) highly integrated microelectronics capable of surviving high-g impact and operation at extremely low temperatures (see Table 2), and (3) in-situ subsurface data acquisition. However, contact was never established with the DS2 microprobes after Mars entry. The exact cause of this problem has not been determined.

Earth Observing 1

EO1, the third of the New Millennium missions, was launched from Vandenberg Air Force Base on November 21, 2000. This validation flight, depicted in Figure 3 and whose complement of technology advances is shown in Table 3, included three advanced imaging instruments and eight advanced spacecraft technologies. The three instruments, the Advanced Land Imager (ALI), the Atmospheric Corrector (AC), and the Hyperion (hyperspectral imager) were designed to enable a new generation of high-performance, low-mass, low-cost instruments for future Landsat-style measurements obtained by NASA's Earth Science Enterprise. The ALI employs novel wide-angle optics and a highly integrated spectro-meter with a panchromatic channel.

Table 2. Planned Technology Validations by DS2

Technology Validated	Key Technology Advance
3-D Microcontroller	Low mass and volume microcontroller capable of surviving high shock loads (30,000 Gs) and low temperatures (-120 °C).
Low-Temp Battery	Ultra-low-temperature energy storage with lithium thionyl chloride batteries capable of surviving very high shock (60,000 Gs).
Power Microelectronics	CMOS mixed digital and analog ASIC used for linear and switching regulators and capable of surviving high shock (30,000 Gs) and low temperatures (-120 °C).
Aeroshell Entry System	Validate advanced, extremely lightweight, non-ablative heat-shield material.
Flexible Interconnect System	Validate Pyralux-based multiplayer circuit carrier and interconnect technology designed for a factor of 10 reduction in mass and volume, yet capable of sustaining high shock and vibration loading.
Drill & Soil Microprobe	Low-power (1.5 W), subsurface micro-motor and microdrill soil sampler capable of surviving high shock (30,000 Gs) and low temperatures (-120 °C).

Figure 3 - EO1. This spacecraft validated technologies contributing to the reduction in cost of future Landsat missions.

Table 3. Technologies Validated by EO1

Technology Validated	Key Technology Advance
Enhanced Formation Flying	Validate of flight software capable of autonomously planning, executing, and calibrating routine spacecraft maneuvers to enable two or more spacecraft to detect errors and cooperatively agree on appropriate maneuvers to maintain desired positions and orientations with minimum ground support.
Pulsed Plasma Thruster	Validate low-mass, low-cost electromagnetic propulsion unit that uses solid Teflon propellant. Thruster delivered very high specific impulse (650–1400 s) with very fine impulse bits (90 – 1000 micro Newton-s) at low power (12–70 W).
Wideband Advanced Recorder Processor	Validate high data rate, high density, low-mass, solid-state recorder with X-band modulation capability. Three-dimensional stacked memory devices and "clip-on-board" bonding used to obtain extremely high-density memory storage.
LA-II Thermal Coating	Validate a special low-absorptance thermal control coating to allow radiators to run cooler and hence more efficiently when in an ultraviolet environment.
Lightweight Flexible Solar Array	The Lightweight Solar Array employs Shape Memory Alloy for shock free deployment, flexible thin-film photovoltaic technology (copper indium diselenide) for energy conversion, and lightweight flexible cable technology derived from Mutifunctional Structures (MFS) to collect and transmit electrical energy from the solar array to the spacecraft.
Carbon-Carbon Radiator	Validate the carbon-carbon facesheet material for honeycomb core radiator panels, while taking advantage of the high thermal conductivity and good strength and weight characteristics of the carbon-carbon material.
X-Band Phased Array Antenna	Future Earth-science missions will produce terabit daily data streams. The antenna enables lower cost weight and higher performance science downlinks; lower cost and size ground stations; and more flexible operations.
Advanced land Imager	Novel wide-angle optics and highly integrated multispectral and panchromatic spectrometer for mass, power, and complexity reduction.
Atmospheric Corrector	Wedge-filtered instrument to increase accuracy of surface-reflectance estimates in 0.85 to 1.5 micron range to correct for water-vapor absorption.
Hyperspectral Imager	High resolution hyperspectral imager capable of resolving 220 spectral bands from 0.4 to 2.5 microns with 30-m resolution.

3. SECOND GENERATION VALIDATION FLIGHTS

The second-generation validation flights started a new paradigm in NMP's experiment selection process. Prior to the paradigm shift, NMP missions would draw experiments from a pool of technologies identified by an integrated product development team. The process was restructured for second-generation flights to emphasize open competition and broadly announced peer reviews on a project-by-project basis. The "Space Technology" theme replaced the "Deep Space" notation and emphasis shifted from stand-alone missions to partnerships for access to space.

Space Technology 5

ST5 is the introductory mission for the second generation of validation flights and will fly in a highly elliptical orbit a group of three miniature (~22 kg) spacecraft, each incorporating seven advanced technologies. The ST5 Nanosat Constellation Trailblazer mission is scheduled for launch (as a secondary payload) in the 2004 to 2005 time period, pending selection of launch vehicle. The ST5 NMP flight, in addition to validating a design process for miniature spacecraft, will validate the suite of advanced technologies presented in Table 4. This mission will also validate manufacturing methods needed to produce large numbers of capable, low-cost spacecraft [5].

ST5 marks the first mission where NMP required all technologies being advanced to be at TRL 5 at the end of the formulation phase. With this imposed constraint, NMP had to be clear on what was meant by TRL 5 within NMP, making it necessary to set boundaries on the other TRLs as well. There were originally many concepts selected for ST5, but several were not at the minimum TRL 3, when initially considered and were thus excluded. The early stages of ST5's selection process necessitated the standardization of TRL criteria; hence the effort to better define TRLs for use by NMP projects began in earnest.

Earth Observing 3

The EO3 mission will fly the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) and six other advanced technologies to enable improved remote sensing of clouds, moisture, and winds in the Earth's atmosphere. These capabilities are needed for improved weather forecasting and to provide additional constraints on atmospheric trace gases. GIFTS will be carried to geosynchronous orbit in late 2004 as a secondary payload on a satellite provided by the US Department of the Navy (DoN). The EO3 mission will provide a system-level validation of the advanced technologies presented in Table 5.

4. FUTURE NMP FLIGHT OPPORTUNITIES

The first and second generation NMP flights (summarized above) were designed to provide a comprehensive, *system-level* validation of suites of interacting technologies. This technology validation approach is essential in some circumstances, but it is not necessarily the most efficient approach for other technologies. For example, the

Table 4. Planned Technology Validations by ST5

Technology Validated	Key Technology Advance
Propulsion System Components	Cold gas microthruster that operates at 3.3 VDC bus voltage and consumes < 1 W peak.
Ultra Low Power Demonstration	Demonstration of 0.25 V CMOS Ultra Low Power Radiation Tolerant logic. Demonstration will be in the form of a Reed Solomon encoder ASIC.
Li-Ion Battery for Small Satellites	Integration of multiple mass-produced (low cost) lithium ion batteries in series-parallel to form compact, low-mass, spacecraft battery packs.
Variable Emittance Coatings for Thermal Control	An electrically tunable coating that can change its properties from absorbing heat when the spacecraft is cool to reflecting or emitting heat when the spacecraft is in the Sun.
Communication Components for Small Spacecraft	Validate a 300-gram nanosat X-band transponder that is 9 times smaller and 12 times lighter than previous comparable systems.
Constellation Communications & Navigation Transceiver	The ST5 transponder is intended for small, low mass, low power satellites that operate outside of the GPS environment but not in the DSN environment. It is for Category A missions, those within 2 M Km from the Earth, usually very close to the Earth.
Multi Function Structures	Validate a novel method of connecting electrical lines that saves 1 kg per 1000 connections.
Autonomous Ground Station Scheduling and Orbit Determination Software for Constellations of Small Satellites	Validation of software designed to enable the ground data system and ground network to gather the nanosatellite tracking data and coordinate autonomous ground contact schedules.

Table 4. Planned Technology Validations by EO3

Technology Validated	Key Technology Advance
GIFTS Instrument	Validate cryogenic imaging interfoerometer with spatial sampling systems optimized for two-dimensional imaging.
Low-Mass, Low-Power Cryocooler	Miniaturized lower-weight, more-efficient, dual-cold head, pulse-tube cryocooler.
Large-Area, Long-Wave IR Focal-Plane Array	Validate improved spectral response with 70% quantum efficiency out to 15 μm, with sensitivity to 16 μm.
Large-Area, Visible, Focal-Plane Array	Validate ultra-low-power, 512 × 512 pixel single-chip, CMOS Active Pixel Sensor imager.
High-Speed, Ultra-Low-Power, Analog-to-Digital Conversion Systems	ASIC-implemented, radiation-hardened, ultra-low-power, 14-bit analog-to-digital converter.
Radiation-Hardened Processors for On-Board, Real-Time Signal Processing and Data Compression	Validate small, low-power, latchup-immune instrument controller with stacked-memory array, all with composite-enclosed or spray-on radiation shielding.
Lightweight Optics and Structures	Validate lightweight silicon carbide mirrors and composite telescope structures with high specific stiffness, excellent thermal stability, and low coefficient of thermal expansion.
Autonomous Pointing and Control	Highly accurate low-mass and volume, ultra-low-power, celestial sensor to enable geo-location and precise short-term navigational knowledge allowing accurate, time-sequential, frame-to-frame registration.

combination of the ion propulsion system, the SCARLET concentrator arrays, and the Autonav system was a particularly expedient approach for validating the DS1 solar electric propulsion system. However, the majority of component and subsystem technologies currently in development could be successfully validated individually on a broad range of platforms.

In order to accelerate the rate of technology infusion into future missions, NMP's existing system-level validation flights were subsequently augmented with a lower-cost, quick-turnaround "subsystem mode" that would include stand-alone validations of a variety of payloads, ranging from components to complete subsystems. These flights would focus specifically on technologies that:

- Require a validation in space to mitigate risks to first users,
- Enable critical measurements or spacecraft capabilities,
- Stand alone, without extensive interactions with other components or payload elements.

By focusing on specific components requiring flight validation, NMP aspires to accelerate the validation rate by providing an environment for components to be flown on the first available flight. The first subsystem validation project selected for the NASA Office of Space Science was Space Technology 6 (ST6). ST6, which became a Project on October 23, 2001, comprises the following three experiments, all of which are dedicated to autonomy: the Autonomous Sciencecraft Experiment, the Autonomous Rendezvous Experiment, and the Inertial Stellar Compass. Scheduled to fly on three different spacecraft that will be launched between 2004 and 2006, ST6 will validate technologies that improve a spacecraft's ability to:

- Make intelligent decisions on what information to collect, and from that, what to send back to Earth
- Rendezvous with other space objects
- Determine its attitude using little power and mass

The common objective of all three experiments is to free the spacecraft from its need for a continuous ground link and shift the decision-making to the spacecraft itself. The technologies that will be validated are listed in Table 6.

Table 5. Planned Technology Validations by ST6

Technology Validated	Key Technology Advance
Autonomous Rendezvous in LEO	Validate ability to rendezvous and perform proximity orbital operations in the region of a cooperative space object.
Inertial Stellar Compass	Validate ability to use micro gyros to provide precision three-axis control of a spacecraft at low power and low mass.
Autonomous Sciencecraft Experiment	Validate ability to autonomously monitor science data, reduce the downlink data requirements, and replan science observations using on-board software.

NMP is also continuing system-level validation flights, and Space Technology 7 (ST7) is the first system-level validation in this new cycle. ST7, a disturbance-reduction experiment to validate the technology advances needed for future gravity-wave experiments or separated-spacecraft systems that require precision position control, became a Project on April 12, 2002. This experiment will attempt to validate spacecraft position control to within a fraction of a wavelength of light, a requirement for separated-spacecraft interferometers that do not use internal delay lines. The specific goal for the ST7 experiment is to validate the capability to fly a trajectory influenced only by external gravity forces to less than $3x10^{-14}$ m/s^2/√Hz from 1 to 10 MHz. The technology to be validated by ST7, described in Table 7, will be directly applicable to the Laser Interferometer Space Antenna (LISA) where low acceleration noise is needed for the study of general relativity, planetary gravity, and gravitational waves.

Table 6. Planned Technology Validations by ST7

Technology Validated	Key Technology Advance
Gravitational Reference Sensor	Validate test mass noise is less than 3×10^{-14} m/s2/√Hz within 1 to 10 MHz, and measure position to < 3 nm/√H within 1 MHz to 10 MHz.
Micro-Newton Thruster	Control thrust to within 1 μN and 25 μN, control precision to within 0.1 μN, and noise to less than 0.1 μN/√Hz between 1 MHz to 10 MHz.

NMP anticipates that technologies for subsystem validation flights will be solicited about once a year, while system-level flights will be conducted at intervals of 18 months to 2 years.

5. Technology Readiness Levels For NMP Validation Flights

Introduction

Technology advances do not occur and mature in an orderly or even predictable manner, and they certainly do not occur in regular, well-organized steps. Still, the progress of a technology advance from that first glimmer of inspiration to its implementation on an operational spacecraft can be conceptualized as progress on a road toward ever increasing understanding, modeling fidelity, and confidence. The technology readiness levels represent milestones demarking progress along that road. The descriptions that accompany each TRL are used by the NMP to determine when that milestone has been reached; they are intended to serve as "exit" or "graduation" criteria.

The linear metaphor of a road is not a perfect one. On a road every milestone must be passed to go from one end to another. During technology maturation, one or more TRLs may be skipped because they are not appropriate to the technology advance at hand, thus emphasizing the need for judgment and insight in the business of advancing space technology.

TRLs are intended to describe increasing levels of technological maturity as an advanced technology progresses from an initial idea to a flight-quality device. They are not applicable to assessing the engineering or development maturity. Consider an S-Band transmitter, an item that has been built and used in space for close to 40 years. The design and fabrication of a new S-Band transmitter is at a high level of technological maturity, even though a particular design has just begun. In assessing the maturity of an advanced technology, it is important to identify the technology advance before attempting to assess its TRL. If there is no advancement, then the technology is mature and has a high TRL rating, regardless of the immaturity of the development of a specific device.

The TRLs described below are the same ones that have long been in general use in NASA. Added to their description are criteria used by NASA's NMP to determine when a particular TRL has been reached. Inherent in the perspective taken by NMP is the thought that both testing and analytical modeling of a technology advance are necessary for the physics associated with that technology advance to be well understood and for its scaling to a broad range of applications to be addressed with confidence. Consequently, increasingly mature TRLs call for increasingly mature and higher fidelity analytical modeling or simulation of the technology advance. These descriptions below are not intended to tell a technologist or the manager of a Project in the NMP just "how" to determine when a particular advanced technology has achieved a particular TRL. Instead, they are intended to provide a framework within which an individual technology provider and a Project Manager charged with the validation of that technology advance can define at the outset of the Project just what constitutes achievement of each TRL. The Project, in its Technology Validation Plan, will document these agreements in sufficient detail that an outside observer can determine that the "exit criteria" have been satisfied and a specific TRL achieved.

When discussing the TRLs, some key words and phrases remain ambiguous intentionally. Their appropriate definition depends on the technology advance being considered and on the needs of the first operational user of that technology advance. For the NMP these ambiguities are resolved during the planning phase of each Project. Consider, for example, "Breadboard" and "Prototype." Both are words that describe different levels of test-article fidelity as compared with the final, flight version of the technology advance. "Breadboard" is meant to convey a bench-top implementation in which all key mechanical and electrical interfaces are simulated; but where form, fit, and scale are not considered. "Prototype" is meant to be an initial implementation having the correct form, fit, function, and scale, but not necessarily having flight quality. For the NMP, the detailed definition of what is meant by these words is to be negotiated with the appropriate NMP PM.

Another example is "Environment," a word used often in the descriptions of TRLs. As used in these definitions, it refers to the spectrum of operating conditions, interfaces (mechanical, electrical, and data), and design conditions (e.g., packaging, miniaturization) to which the technology advance will be exposed both during testing and during flight operations. "Relevant environment" is a subset of all the "environments" to which the technology advance will be exposed. For the NMP, "relevant environment" is defined to be that environment, operating condition, or combination of environments and operating conditions that most stresses the technology advance and is consistent with that expected in the spectrum of likely initial applications. In a specific instance in the NMP, it is to be delineated in detail with the appropriate NMP PM and concurred by the NMP Program Manager.

Figure 4 is a depiction of the TRL progression showing the specific region relevant to the New Millennium mission.

TRL 1: *Basic* principles *observed and reported*

This is the lowest "level" of technology maturation. At this level, conceptualization and scientific research transitions to applied research and development and a new technology advance begins the journey to technological maturity.

TRL 2: *Technology concept and/or application formulated*

Once basic physical principles are observed, then at the next level of maturation, practical applications of those characteristics can be "invented" or identified. TRL 2 is characterized by identified applications in which the technology advancement can be shown analytically to offer significant, quantifiable benefits as compared with the existing state of the art. It is this elucidation of potential benefit that spurs the investment necessary to carry the technology advancement to higher TRLs.

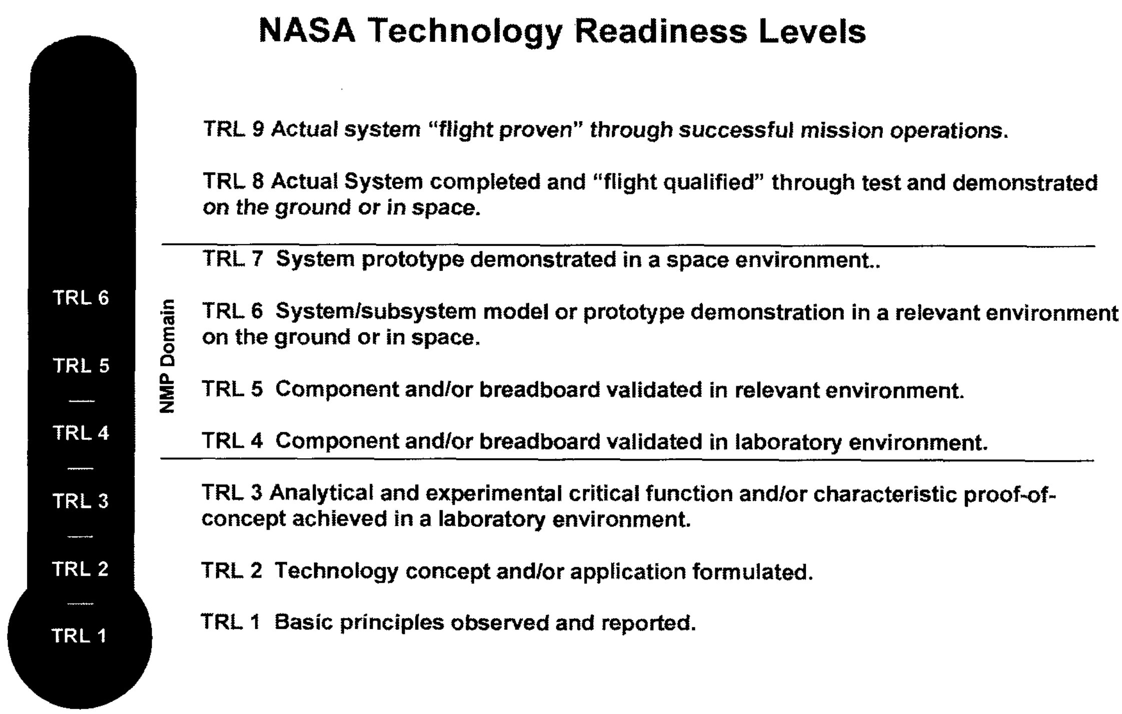

Figure 4 - NMP flight-validates technologies that have initially matured to TRL 4. After flight validation, the technology level is TRL 7.

To be at TRL 2, the technology advance will satisfy several conditions:

1) Potential applications for the technology advance have been described.
2) The quantitative benefit offered by the technology advance to the applications has been assessed analytically.

TRL 3: *Analytical and experimental critical function and/or characteristic proof-of-concept achieved in a laboratory environment*

At this step in the maturation process, active research and development (R&D) is initiated. This includes both analytical studies to set the technology into an appropriate context and laboratory-based studies to validate empirically that the analytical predictions are correct. These studies and experiments validate the benefits offered by the technology advancement to the applications/concepts formulated at TRL 2.

To be at TRL 3, the technology advance will satisfy several conditions:

1) Laboratory tests have demonstrated that the technology advance performs generally as predicted by the analytical model and has the potential to evolve to a practical device.
2) Analytical models both replicate the current performance of the technology advance and predict its performance when operating in a breadboard environment.
3) A determination of the "relevant environment" for the technology advance has been made.

TRL 4: *Component and/or breadboard validated in a laboratory environment*

Following successful "proof-of-concept" work, basic technological elements must be integrated to establish that the "pieces" will work together to achieve concept-enabling levels of performance for a component and/or breadboard. This validation must be devised to support the concept that was formulated earlier, and should also be consistent with the requirements of potential system applications. The validation is relatively "low-fidelity" compared with the eventual system; it could be composed of *ad hoc* discrete components in a laboratory.

To be at TRL 4, the technology advance will satisfy several conditions:

1) A "component" or "breadboard" version of the technology advance will have been implemented and tested in a laboratory environment.
2) Analytical models of the technology advance fully replicate the TRL 4 test data.
3) Analytical models of the performance of the component or breadboard configuration of the technology advance predict its performance when operated in its "relevant environment" and the environments to which the technology advance would be exposed during qualification testing for an operational mission.

TRL 5: *Component and/or breadboard validated in a relevant environment*

At this TRL, the fidelity of the environment in which the component and/or breadboard has been tested has increased significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the entire complement (whether component-level, sub-system level, or system-level) can be tested in a "relevant environment".

The difference between TRL 4 and TRL 5 is found in the level of stress applied to the advanced technology during test. To be tested successfully in a "relevant environment", the quality of the component or breadboard may have to be improved significantly from that tested at the TRL 4.

To be at TRL 5, the technology advance will satisfy several conditions:

1) The "relevant environment" is fully defined.
2) The technology advance has been tested in its "relevant environment" throughout a range of operating points that represents the full range of operating points similar to those to which the technology advance would be exposed during qualification testing for an operational mission.
3) Analytical models of the technology advance replicate the performance of the technology advance operating in the "relevant environment."
4) Analytical predictions of the performance of the technology advance in a prototype or flight-like configuration have been made.

For some technology advances, testing in space is the only means by which the technology advance can experience its "relevant environment" For example, consider deployment or control of a solar sail. In these cases TRL 5 must be accomplished analytically. A model that describes the technology advance's relevant physics, chemistry, and engineering and that replicates all the experience gained from testing on Earth can be used to predict the performance of the technology advance in the appropriate "relevant environment." This model and its predictions then become the demonstration of operation in a "relevant environment."

TRL 5 is important to the NMP Process because its achievement is a condition of successful confirmation and the consequent start of the Implementation Phase. A clear, unambiguous, specific definition of that which constitutes achievement of TRL 5 for a specific technology advance is to be delineated with the applicable PM during the formulation phase of the Project. The PM will obtain the concurrence of the NMP Confirmation Assessment Review Board and the NMP Program Manager.

An example of a technology reaching TRL 5 might be the long-wavelength focal-plane array to be flown on EO3. This component was validated in thermo-vacuum at a temperature of 60 K out to a wavelength of 14.85 μm. The thermo-vacuum conditions comprising the relevant environment were well understood and fully defined. Achieving stable performance at long wavelengths for HgCdTe photodiodes is very difficult, and the new technology was the achievement of its spectral performance at this wavelength.

TRL 6: *System/subsystem model or prototype demonstration in a relevant environment on the ground or in space*

A major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative model or prototype of the subsystem or system, well beyond *ad hoc*, "patch-cord" or discrete-component-level breadboarding, would be tested in a "relevant environment." However, commercial parts are still appropriate where not contra-indicated by the environment in which they will be tested. At this level, if the only "relevant environment" is space, then to achieve TRL 6 the model/prototype must be successfully validated in space. An example of this situation is the ST7 Disturbance Reduction System where the extreme sensitivity of the instrument to gravity precludes on-Earth prototype demonstrations. However, in many (if not most) cases, TRL 6 can be demonstrated using tests on Earth, and these tests potentially offer a broader range of operating conditions than those conducted in space.

To be at TRL 6, the technology advance will satisfy several conditions:

1) The technology advance is incorporated in an operational model or prototype similar to the packaging and design needed for use on an operational spacecraft.
2) The system/subsystem model or prototype has been tested in its "relevant environment" throughout a range of operating points that represents the full range of operating points similar to those to which the technology advance would be exposed during qualification testing for an operational mission.
3) Analytical models of the function and performance of the system/subsystem model or prototype, throughout its operating region and in its most stressful environment, have been validated empirically.
4) The focus of testing and modeling has shifted from understanding the function and performance of the technology advance to examining the effect of packaging and design for flight and the effect of interfaces on that function and performance in its most stressful environment.

TRL 7: *System prototype demonstrated in a space environment*

TRL 7 can be a significant step beyond TRL 6 toward increased fidelity, requiring both an actual system prototype and its demonstration in a space environment. Because of cost, it is a step that is not always implemented. In the case of TRL 7, the prototype should be at the same scale as the planned operational system and its operation must take place in space. However, since the objective of the TRL 7 experiment is to validate the technology, scaling of the experiment—if supported by modeling—would be acceptable. An example of this would be a flight validation of a sub-scale solar sail. The driving purposes for achieving this level of maturity are to assure that system engineering is adequate, that trans-interface interactions are adequately modeled and understood, and that in-space operation at the appropriate scale is both as expected and as understood, and that in-space operation at the appropriate scale is both as expected and as predicted. Therefore, the demonstration must be of a prototype of that application. While not all technologies in all systems will require an in-space test, the actual test of a system prototype in a space environment would normally be performed in cases where the technology and/or subsystem application is both mission critical and high risk.

TRL 8: *Actual system completed and "flight qualified" through test and demonstrated on the ground or in space*

All technologies being used on operational spacecraft achieve TRL 8. For most technology advances, TRL 8 represents the end of true "system development".

TRL 9: *Actual system "flight proven" through successful mission operations*

All technologies being applied on operational spacecraft achieve TRL 9. This includes integrating the new technology advance into an existing system and achieving successful operation during a science mission. This TRL does not include product improvement of ongoing or reusable systems or the evolutionary improvement of technology advances already at TRL 9.

6. SUMMARY

Technology validation for future NASA science missions is a complex process that requires careful planning, coordination, and execution. NASA created the NMP in 1995 to address these technology validation needs of the NASA Office of Space Science and Office of Earth Science. In this paper we have described how the NASA TRLs are interpreted by the NMP. As the NMP Program matured through its earlier stages to its present state, it became obvious that a more rigorous and consistent understanding be developed for the states of technology necessary for NMP flight validation. Technology advances must have attained a minimum level of technological maturity to be candidates for in-space validation by the NMP. To assess that maturity, the NMP has elaborated the definitions of the TRLs long in use by NASA. To the existing definitions the Program has added, for its own use, criteria with which to judge whether a technology advance has attained a specific TRL. We presented a summary of the first and second generations of the NMP missions and their associated suites of technologies in order to put the need for a consistent interpretation into perspective. As one final reminder, the TRL refers to the maturity of the technology, not to the specific development stage of a given item. That factor is important in the final selection of technologies for flight validation.

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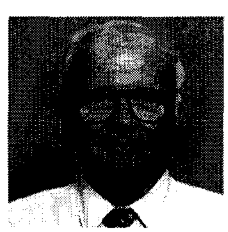
BIOGRAPHIES



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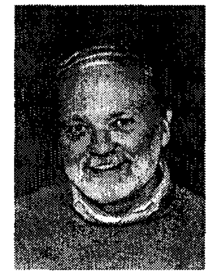

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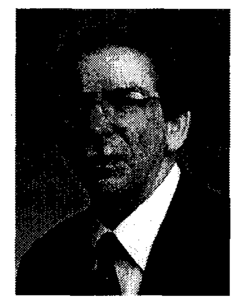

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